Report of the GeoPRISMS Synthesis Theoretical and Experimental Institute

February 26-March 1, 2019. Menger Hotel, San Antonio, TX

Lead Conveners of Organizing Committee:
Harm Van Avendonk (University of Texas, Austin)
Katherine A. Kelley (University of Rhode Island)

Co-Conveners:
Josef Dufek (University of Oregon)
Rob Harris (Oregon State University)
Ikuko Wada (University of Minnesota)
Jessica Warren (University of Delaware)
Phil Skemer (Washington University)
Kyle Straub (Tulane University)
Demian Saffer (Pennsylvania State University; ex officio)

Early Career Symposium Conveners:
Taryn Lopez (University of Alaska)
Eric Mittelstaedt (University of Idaho)

Summary

Scientists and students participated in the February 26-March 1, 2019 GeoPRISMS Synthesis TEI in San Antonio to evaluate progress on the science goals, and to determine the steps that must be taken towards a successful completion of the decadal program. In both the Rift Initiation and Evolution (RIE) and Subduction Cycles and Deformation (SCD) initiatives, high-quality data sets have been gathered to address important science questions. Some of these field programs were developed by small groups of investigators. A few other large data sets were acquired in Community Experiments, which made very good use of logistical support and national facilities. Over the years, the staged funding model for the five Primary Sites has helped the planning of these community experiments, but this strategy also implied that research in some of the Primary Sites progressed more quickly than in others. Leveraging of other research programs such as Earthscope and IODP has enhanced the success of GeoPRISMS. Over the course of three days, the participants reviewed science progress in three themes: Deformation at all Time Scales, Mass Fluxes, and Geohazards. The main meeting was preceded by a one-day Early-Career Symposium. The current state of science was presented in a series of keynote talks. In a few breakout sessions, participants discussed where there are still gaps in our research. Since the analysis of GeoPRISMS data and numerical modeling efforts are still underway, much of the integration and synthesis of the GeoPRISMS program will occur in the last two years. The community emphasized the importance of multidisciplinary research. One of the important needs of scientists and students after the GeoPRISMS program is therefore the opportunity to participate in small workshops where colleagues from various research disciplines meet to address focused science questions.

1. Introduction

GeoPRISMS is a community-driven program to understand the geological processes that are active across continental margins. Scientists and students from a wide range of disciplines are strongly engaged in the two major initiatives of this program, Rift Initiation and Evolution (RIE) and Subduction Cycles and Deformation (SCD). The RIE initiative has two Primary Sites in Eastern North America (ENAM) and the East African Rift System (EARS). The Primary Sites for SCD are Cascadia, the subduction zone of Alaska and the Aleutians, and New Zealand. Since many of the science questions are complex, they lend themselves to an interdisciplinary science approach, often using data from more than one primary site. The GeoPRISMS Synthesis & Integration Theoretical and Experimental Institute (TEI) offered a great opportunity for scientists and students to exchange ideas, enhance collaborations, and to identify opportunities for future research.

The Synthesis & Integration TEI was held at the Menger Hotel in San Antonio, TX from Feb 26-Mar 1, 2019, fittingly the same site as the MARGINS Successor Planning Workshop that initially defined the scope of the GeoPRISMS program in 2010. Objectives of the meeting included summarizing progress on GeoPRISMS science over the past decade, defining the future efforts needed to integrate and synthesize the multi-disciplinary outcomes of the program, and positioning the community for an engaging and sustainable future beyond the end of GeoPRISMS. To achieve these goals, we assembled a diverse team of conveners, speakers, and group leaders, and developed an agenda that focused on science themes common to both the Rift Initiation and Evolution (RIE) and Subduction Cycles and Deformation (SCD) Initiatives of the GeoPRISMS program. The meeting attracted 170 participants, 70 of which were students and post-docs, and >100 participants brought posters for presentation during cash bar events in the evenings or during coffee breaks during daytime sessions.

In the 2019 Synthesis TEI, participants had two additional charges: What do we envision as the key products and achievements of the GeoPRISMS program? How will the community keep the momentum in interdisciplinary research across plate boundaries, after the completion of the decadal program? Research on the evolution of rifts and convergent margins face similar challenges, and the interactions between all scientists that are active in the two initiatives was considered a great benefit of the meeting.

The meeting structure aimed to bring the RIE and SCD communities together through a series of paired keynote talks under unifying themes of Deformation at all Timescales, Mass Fluxes, and Geohazards. Early-career participants engaged in a half-day pre-TEI symposium, and led breakout discussions and reporting to the main group during the TEI. Together, this mix infused the meeting with both legacy and fresh perspectives on how far our science has come and where our community should go in the future. Short talks on allied science programs, data legacy, education and outreach, and models/programs for future community engagement set the stage for discussions of GeoPRISMS synthesis and consideration of ways our community could move forward.

2. Early-Career Symposium

As part of the lead up to the GeoPRISMS TEI 2019, a half-day Early Career Symposium was held on February 26th. The primary goals for the ECS were to: 1) provide opportunities for early career researchers to network across GeoPRISMS disciplines, and 2) provide these researchers with advance exposure to TEI themes and questions to deepen their overall workshop experience and facilitate their participation in larger group discussions. There were 64 participants from a variety of specialties including rock mechanics, geodynamic modeling, seismology, geochemistry, structural geology, geodesy, and magnetotellurics. Within the themes of the GeoPRISMS TEI, most participants self-identified their research interests into either the Deformation on all Timescales or Mass Flux themes, with a relatively small number of participants identifying Geohazards as their primary research theme.

To facilitate the primary goals of the ECS, the symposium was organized around a series of talks and group breakout sessions. Each talk was assembled by a multi-disciplinary team of three to four early career participants. They invited researchers from a range of disciplines, who assembled broad overview presentations for each TEI theme. Following each talk, the participants split into pre-assigned discussion groups (14-18 people) to ensure representation from all three research themes that were tasked with addressing two questions: 1) what are the remaining or emerging science questions related to this TEI theme, and 2) what infrastructure, data and/or synthesis do we need to address these science questions? In each group, questions were discussed by hierarchical groupings where first a pair of participants would discuss the question, then four participants, then eight participants, and finally the entire group. During each discussion interval the pair or group was asked to select the most important question or synthesis goal discussed. This style of breakout group was chosen to provide the best opportunity for all voices to contribute to discussions and to manage the range of questions and the number of objectives. In the end, each breakout group identified four primary or key points that address the above questions and then reported these responses to the group. The responses were synthesized by the ECS organizers and presented to the larger TEI. The synthesized responses for each theme can be found below.

During the ECS, a survey was distributed to gauge the impacts of GeoPRISMS on the careers and career paths of early career researchers. The first two questions asked about participation in the GeoPRISMS program. Of the responses received, 43% of the ECS participants were currently or had been funded in part to conduct GeoPRISMS research and 80% of participant responders had attended a meeting, workshop, and/or field program funded by GeoPRISMS (not including the current ECS or the TEI). When asked the benefits of the GeoPRISMS program on the ECS participant's careers, common responses included providing a forum for networking and collaboration, exposure to science questions and multidisciplinary science, and opportunities to participate in field and/or laboratory programs. Feedback from Early-Career Scientists on the three themes of the GeoPRISMS Synthesis and Integration TEI includes the following priorities:

Deformation at all timescales: There is a need for time series data to observe changes and sudden events that might not otherwise be captured. Interdisciplinary collaboration and open-access data should be fostered. Rock mechanics experiments must be expanded to refine physical material properties. Data acquisition campaigns must fill gaps, such as offshore subduction zones,and cover multiple spatial scales.

Mass Fluxes: Geophysical and geochemical data should be integrated to improve our understanding of mass fluxes. New constraints on the temporal and spatial variations in rheology and permeability of the oceanic crust and lithosphere are needed. Methods for scaling of localized processes to plate boundaries is necessary to allow local-scale data to inform large-scale processes. Dense sensor networks from the seafloor to the surface are strongly desired.

Geohazards and Margin Stability: Effective communication on baseline hazard threats between the general public and policy makers at the federal, state, and local levels should be facilitated through our science community. Dense monitoring arrays are needed, especially in hazard prone areas. A framework and tools to facilitate interdisciplinary collaboration should be developed prior to significant events (e.g., the recent Kilauea eruption) to maximize research and science. We need coupled deterministic and probabilistic hazard models that include information from geophysical and geochemical sources.

3. Structure of the main meeting

Day 1 (February 27). The TEI launched with two summary talks by Donna Shillington and Sarah Penniston-Dorland, summarizing the diverse array and current status of studies funded by GeoPRISMS in the RIE and SCD Initiatives, respectively. These overviews incorporated outcomes of the two previous initiative-specific TEI workshops that took place in recent years. Eric Mittelstaedt and Taryn Lopez summarized the outcomes of the ECS to set the stage for further TEI discussions. Short talks from allied science organizations also helped to frame ideas for community engagement beyond GeoPRISMS. Ben Phillips (NASA Earth Science) gave an overview of the Earth-focused programs at NASA with particular emphasis on remote sensing capabilities and how these dovetail with GeoPRISMS science themes. Joan Gomberg and Nathan Miller (USGS) addressed natural collaborations with the GeoPRISMS community with regard to natural hazard assessment and mitigation. Sue De Bari updated the group on the connections between IODP and GeoPRISMS science under the current IODP science plan, and also opportunities to influence future IODP science priorities as they develop a science plan for post-2023 work. Suzanne Carbotte (IEDA) also spoke about the resources available for GeoPRISMS-related data preservation and access through the IEDA Data Repository.

The central structure of the workshop drew upon paired keynote talks that addressed themes common to both the RIE and SCD initiatives. Under the theme of 'Deformation at all Time Scales,' keynote speakers Jolante van Wijk (RIE) and Mark Reagan (SCD) addressed the role of structural inheritance in plate tectonic events, and Cindy Ebinger (RIE) and Jeff Freymuller (SCD) spoke on topics relating to reconciling strain budgets at different time scales. Following these talks, four separate breakout groups led mostly by early-career participants, discussed shortcomings of current data sets and Earth models, goals of a GeoPRISMS synthesis, and setting the stage for future community-driven science.

Day 2 (February 28). The second day of the TEI began with summaries of the discussions from breakout sessions the previous day, given by early-career participants in each session. Under the TEI theme "Mass Fluxes," keynote talks from Tobias Fischer (RIE) and Terry Plank (SCD) addressed major findings and new directions of research in fluid and volatile fluxes at plate boundaries, and Donna Shillington (RIE) and Jim Gill (SCD) spoke about the evolution of crustal composition at rifting and subducting plate boundaries. Overview talks from PIs and coordinators of three NSF-funded Research Coordination Networks (RCN) offered perspectives on focused efforts to develop new connections within the community and move GeoPRISMS-aligned science forward. Harold Tobin updated the participants on the status of the SZ4D RCN, which strives to develop a new decadal program supporting subduction zone science, Gabriel Lotto spoke about the Modelling Collaboratory for Subduction Zone Science RCN, which aims to build a multi-scale, multi-physics numerical modeling community, and Tobias Fischer informed the meeting about the Community Network for Volcanic Eruption Response (CONVERSE).

An afternoon breakout session asked groups to identify topics or themes for a future synthesis workshop, and to articulate a clear rationale for why the community needs a focused effort to synthesize the topic, including the role of GeoPRISMS data sets. Groups further discussed other activities, beyond workshops, that would help to accomplish GeoPRISMS synthesis or enhance interpretations of existing data, and specifically addressed the key aspects of the GeoPRISMS program that would be essential to preserve beyond the end of the program. Early-career participants presented the outcomes of these discussions to the main group, and from these emerged a set of key science topics that further informed the final discussions of the TEI on Day 3.

In the late afternoon, a final science session of keynote talks addresses topics under the theme 'The Stability of Margins and Geohazards.' Doug Edmonds (RIE) and Juli Morgan (SCD) addressed feedbacks between tectonics, surficial processes, sediment transport and deposition, and Brandon Dugan (RIE) and Sue Bilek (SCD) presented overview talks on geohazards from the perspectives of landslides and great earthquakes.

Day 3 (March 1). The final day of the TEI opened with a breakout session focused on the suite of science topics that emerged from the previous breakout sessions. Participants were asked to self-organize under one of the topics on the list, and to choose an early-career participant in the group to be their leader, with the goal to produce one slide that illustrates a way to motivate synthesis of the chosen topic. Later in the morning, these leaders presented the outcomes of their breakout topic discussion to all TEI participants.

The late morning session provided opportunities for discussion of MARGINS and GeoPRISMS data legacies, and a panel discussion led by Juli Morgan, Sarah Penniston-Dorland, Jeff Marshall, and Bob Stern provided insight into the Education & Outreach efforts accomplished under MARGINS, as well as informative overviews of E&O efforts underway through GeoPRISMS.

Following breakout session reports, the full group wrapped up the meeting with discussion of the potential of workshops, or a coordinated series of related workshops, to help achieve GeoPRISMS science synthesis, in addition to other strategies that could further the community's desire to remain cohesive and inclusive, accomplish cutting-edge science, and broadcast our collective achievements as broadly as possible.

4. Status of research in the GeoPRISMS Initiatives

4.1 Rift Initiation and Evolution (RIE):

The Rift Initiation and Evolution Initiative aims to improve our understanding of all temporal stages of a continental rift. The GeoPRISMS community chose the passive Eastern North American Margin (ENAM) and the active East African Rift System (EARS) as two primary sites where most research efforts should be concentrated. The two sites complement each other well. The deep crustal structure and stratigraphy of ENAM contains a complete record of Mesozoic rifting (Dillon and Popenoe, 1988; Holbrook et al., 1994; Withjack et al., 1998). The subsidence of the margins after rifting are an important last stage of its development, since it depends on the thermal evolution of the underlying mantle (Winterbourne et al., 2009). At the EARS, scientists study the interaction of active rifting processes, such as extensional faulting seismicity and magmatism (Ebinger et al., 1993; Rooney et al., 2014). Extension at both primary sites is approximately orthogonal, with well-defined rift segments that have experienced varying degrees of magmatism.

Along the ENAM some important studies focused on post-rift magmatism (Mazza et al., 2017), and the deep mantle structure of the eastern United States, which greatly benfitted from the Earthscope program. Many other goals of the RIE initiative required new high-quality geophysical data, since most products of rifting lie beneath sediments of the coastal plan and offshore along the Atlantic margins. In 2014 and 2015, a community seismic experiment offshore North Carolina produced a combined onshore-offshore, broadband and active-source seismic data set. With this unique data set, scientists can study interactions of geological processes in the mantle, crust and on the Earth's surface, which is essential to meet GeoPRISMS goals. Preliminary results from analysis of this open-access data set show evidence for sediment transport across the continental shelf (Hill et al., 2018), and the emplacement of mafic igneous crust during rifting and continental breakup. Complexities in the structure of the oldest oceanic crust and upper mantle may reflect a prolonged transition from rifting to early seafloor spreading, and possibly post-rift mantle flow (Lynner and Bodmer, 2017).

In the EARS, detailed mapping of Cenozoic igneous activity, modern geodetic data, and deep seismic imaging provide evidence for feedbacks between extensional deformationand magmatism (Nooner et al., 2009; Birhanu et al., 2016; Rooney et al., 2017; Gaherty et al., 2019). The rift system shows a consistent progression in the evolution of the rift from south to north. In the vicinity of Lake Malawi, extensional deformation is dominated by slip along several rift-parallel normal faults (Accardo et al., 2018). In contrast, at the northern end of the EARS extension in the Afar region may be accommodated fully by magmatic diking (Ebinger et al., 2010). Other ongoing research in the EARS explores whether mantle plumes influence extension (Rychert et al., 2012), how preexisting lithospheric heterogeneities control rift segmentation and diversity (Beutel et al., 2010), and how magmas and volatiles interact with extensional fault systems (Muirhead et al., 2016).

4.2 Subduction Cycles and Deformation (SCD)

The Subduction Cycles and Deformation initiative examines the processes and products of active subduction, from initiation through maturation. At a series of planning workshops, the GeoPRISMS community identified three primary sites of focused research at subduction zones: Cascadia, the Alaska-Aleutians system, and New Zealand. These three sites encompass a spectrum of subduction architecture, from continental to oceanic upper plates, and young to old subducting lithosphere, which enable the community to characterize end-member cases of subduction and along-strike variability.

In Cascadia, the continental upper plate and the young age of the subducting plate make it a truly end-member subduction zone. GeoPRISMS work in this region built upon a wealth of prior study and leveraged deployment of an amphibious seismic array through the Cascadia Initiative community experiment. In 2012, the COAST and Ridge-to-Trench projects conducted marine seismic studies to constrain the position and geometry of the Cascadia plate boundary (Canales et al., 2017; Han et al., 2018). In 2013, deployment of thermal probes and fluid flow meters characterized fluid and heat fluxes along the Cascadia megathrust. As an established locality of slow slip events from land-based GPS, offshore work in 2012-2016 used GPS-acoustic seafloor geodesy to measure the slip deficit offshore of the Cascadia margin. The iMUSH experiment (2012-2016) probed the depths of the Mt. St. Helens magmatic system, from slab to surface, using a suite of both geophysical and petrological studies (Kiser et al., 2016; Bedrosian et al., 2018).

The Alaska-Aleutian subduction zone transitions from a continental overriding plate in the east to an oceanic plate in the west. Several key factors, such as incoming plate age and structure, convergence rate and vector, modes of slip, and upper plate composition and structure, make this system well suited to the exploration of along-strike variability in subduction zones. Work in this area leveraged the deployment of the EarthScope transportable seismic array and Plate Boundary Observatory geodetic instrumentation, and developed synergies between the GeoPRISMS community and the USGS, the Deep Carbon Observatory, and EarthScope. In 2015-2016, NSF supported the Joint Platform for Aleutians Research, which enabled field campaigns to remote areas of the Aleutians for sample collection and instrument deployments. Teams collected rock, tephra, and gas/fluid samples, and deployed geophysical and MT instrumentation in remote areas of the Aleutians that would otherwise be difficult to access as stand-alone projects. The 2018-2019 Alaska Amphibious Community Seismic Experiment employed >100 ocean bottom and land-based seismometers to develop a detailed portrait of the megathrust and the downgoing and overriding plate structures in the area of the Alaska Peninsula. Work in this area is also ongoing; in 2019, the EMAGE project will be aboard R/V Sikuliaq to conduct a marine electro-magnetic survey of fluid distribution in the megathrust off the Alaska Peninsula.

New Zealand, where two subduction zones lie along the Pacific-Australian plate boundary, is one of the primary sites for the SCD initiative. In the north, the Hikurangi margin, where subduction of an oceanic plateau formed a subaerial forearc and relatively shallow plate interface, is an important site for studies of slow slip events (SSE), the along-strike transition from creeping to seismogenic slip, and the inputs and outputs of volatiles from the forearc to the backarc. In 2017 and 2018, GeoPRISMS research on the Hikurangi margin leveraged 2-D and 3-D marine seismic studies of subduction zone internal structure with the R/V Marcus Langseth, the HOBITSS marine geodesy and seismology experiment (Wallace et al., 2016), and JOIDES Resolution IODP drilling expeditions 372 and 375. The analysis and integration of these unique data sets is still ongoing. In 2018, the R/V Marcus Langseth also gathered marine seismic reflection and refraction data on the Puysegur Trench, south of New Zealand (Mao et al., 2017). This convergent margin is relatively young (~10 Ma), so it is a location where the geological factors that contribute to initiation of subduction can be investigated

5. Summaries of workshop themes

5.1 Deformation at all Time scales.

Deformation processes are essential to the evolution of the lithosphere / asthenosphere system and therefore strongly influence rifting and subduction. Deformation is driven largely by tectonic forces and facilitated by heat and mass flux. Therefore, within subduction and rift systems, deformation varies both spatially and temporarily. Although the rift and subduction systems are in different tectonic stress regimes, a similar set of microscopic mechanisms likely operates in both systems. However, a complicating factor in the study of deformation is that observational approaches vary depending on the length and time scales of processes that are most relevant to given parts of the system. The first thematic session of the workshop therefore aimed to synthesize recent findings on deformation processes in the two systems, to identify some commonality and consistent understanding of deformation processes in these two systems. Here, we highlight some of the exciting advancements from the RIE and SCD initiatives that were discussed in the session.

Geophysical observations combined with geodynamic modeling indicates that existing micro- and macro-scale structures play an important role in the development of rift and subduction systems. The East African Rift zones have been developing along the margin of the Tanzanian craton, and it is proposed that their development was guided by the lattice-preferred orientation of olivine in the lithospheric mantle that developed during continent assembly (Corti et al., 2007). In contrast, the Rio Grande rift zone cuts into the Proterozoic craton, which has been attributed to edge-driven mantle convection (van Wijk et al., 2008, 2010), controlled by the variations in the slab geometry and the thickness of the overlying lithosphere (Axen et al., 2018) or formed above a gap in the slab. In subduction systems, understanding the formation of protoforearc is critical to their early evolution. The geochemical analyses of volcanic rocks in the forearc of the Izu-Bonin-Mariana (IBM) forearc crust, for example, indicate the formation of the protoforearc in a more organized manner than previously thought [Reagan et al., 2019]. The forearc crust consists of basalt, low-silica boninite (LSB), and high-silica bonitite (HSB). These basalts have been interpreted as the product of early protoforearc spreading that was produced by upwelling of asthenospheric mantle and decompressional melting due to the sinking and rollback of the oceanic plate. This was followed by late protoforearc spreading, producing LSB upon some interaction of the mantle source with slab-derived fluid and then by arc volcanism that produced HSB.

Recent seismic and geodetic observations of rift systems have led to a better understanding of the strain accommodation in the lithosphere and the cycles of amagmatic deformation (faulting/earthquakes) and magmatic deformation (magma intrusion/diking) (**(**Ebinger et al., 2013). Similarly in subduction zones, seismic and geodetic observations, particularly those offshore, have helped to better understand the spatial and temporal relations between slow slip, non-volcanic low-frequency tremor, regular earthquakes, and afterslip. Further, geophysical observations indicate strong correlations between the along-strike variations in the sliding behavior of the subduction interface with fabric orientations in the incoming plate (e.g., Alaska Peninusla (Li and Freymueller, 2018) and availability of free fluids (e.g., Hikurangi (Wallace et al., 2012; Reyners et al., 2017)).

5.2 Mass Fluxes.

Transport of materials from one place to another is a central, unifying theme of GeoPRISMS research. For example, fluid release at plate boundaries influences pore pressure and facilitates deformation, volatiles influence the rheology and physical properties of the crust and mantle, crustal composition evolves as materials physically segregate within it, and sediment transport influences the style and manifestation of rifting and subduction processes. Mass fluxes at rifting and subducting margins involve the movement of volatiles and melts within these systems, the growth or destruction of crust, and the dispersal of sediments. This workshop session highlighted recent research and future directions within this cross-cutting theme.

The movements of volatile-rich fluids, in particular, are crucial to the inner workings of rifts and subduction zones. In the East African rift, the mantle CO2 content is enriched over MORB mantle (Fischer et al., 2009; Anderson and Poland, 2017), and H2O and CO2 contents in excess of a MORB mantle source are required for melting to take place. Mechanisms for sub-continental mantle enrichment in volatiles might involve accretion of arc terranes or passage of enriched mantle plumes (Foley and Fischer, 2017; Currie and van Wijk, 2016). Yet, volatile fluxes at active continental rifts remain poorly constrained, and this topic is ripe for future work incorporating effects of fluids in dynamical modeling, constraining magmatic volatile contents through melt inclusion studies, MT studies to detect fluids or melts in situ, thermobarometry to constrain P-T conditions of magmas and their volatile contents, and an inter-disciplinary synthesis effort focused on the roles of volatiles in rifting. At subduction zones, several recent studies have assessed the state of hydration of the subducting plate, with particular assessing the distribution and importance of serpentinite in the dispersal of H2O throughout subduction zones remains a key goal for future research, spurred by recent geophysical and MT studies (e.g., Shillington et al., 2015). Alternative models of fluid flow (e.g., Wilson et al., 2014) and diapiric ascent (e.g., Vogt et al., 2013) within the mantle wedge have potential consequences for the composition of arc magmas (e.g., Nielsen and Marschall, 2017). Several recent geodynamic studies further focus on the loci, pathways, and thermal consequences of melt transport in the upper reaches of the mantle wedge and overlying crust (e.g., Perrin et al., 2016; Rees-Jones et al., 2018), highlighting a need for imaging of melt at sub-Moho depths. Constraints on the timing of magmatic ascent, storage, and eruption throughout the crust, and the volatile fluxes that accompany these, are within reach with the development of new crystal clocks (e.g., Cooper and Kent, 2014; Rubin et al., 2017; Ruprecht and Plank, 2013) and melt inclusion constraints on magmatic volatile contents (e.g., Walowski et al., 2015). The importance of oxygen fugacity to magmatic and mantle systems is also emerging as a key variable, associated with slab fluxes (e.g., Brounce et al., 2014) and also potentially with seismic properties of the mantle (e.g., Cline et al. 2018). And beyond H_2O, the cycling of C and S through subduction systems (e.g., Kelemen and Manning, 2015), and establishing the input fluxes and efficiency of transfer of these elements through the subduction zone are additional future goals.

The evolution of continental crust, as it is either created or destroyed, is another major consequence of mass fluxes at active margins. Volcanic arcs have added large volumes of new igneous crust over the course of the Phanerozoic (Stern and Scholl, 2010). However, the major element composition of island arcs is more mafic than continental crust, which has a andesitic composition on average. Moreover, many island arcs lack the enrichment in mantle-incompatible elements of the Earth's continental crust. Possibly, intraoceanic arcs can form continental crust directly, if oceanic crust enriched by a mantle plume source subducts (Gazel et al., 2015). The crustal composition can change gradually as the arc matures, by incorporating sediment and ocean-island basalts from the incoming slab. Alternatively, discrete events can also have a profound influence on the structure and composition of volcanic arcs. Arc rifting, anatexis and delamination of arc lower crust will cause the composition of island arcs to become similar to that of continental crust over time.

Volcanic rifts are another setting where new igneous crust is added to continents during plate tectonic events. The amount of mantle melt produced during rifting increases if the mantle potential temperature is elevated, or if the upper mantle is enriched, for example in the presence of a mantle hotspot. Analyses of the ENAM community seismic data set shows that the thickness and composition of the oldest oceanic crust adjacent to rifted margins is consistent with slightly hotter than average mantle temperatures during rifting between North America and West Africa. Since mantle melts can weaken the lithosphere, mantle plumes or hotspots are generally seen as a mechanism to achieve continental breakup (Bialas et al., 2010). However, mantle upwelling will most likely lead to decompression melting where the lithosphere was previously thinned due to stretching. For example, rift basins of the Appalachians, and the South Georgia Rift basins formed in the Triassic (Withjack et al., 1998), but they accumulated volcanic deposits mostly after the Triassic/Jurassic CAMP event, which subsequently triggered the opening of the central Atlantic Ocean (Whalen et al., 2015). Current research in the East African Rift System shows that sutures and older faults have controlled the development of most recent rift basins, where sediments and mantle melts are modifying the composition of the African crust (Ebinger et al., 2017).

5.3 Geohazards.

Subduction and rifting processes can focus a tremendous amount of energy in the near surface and produce some of the most significant geohazards on the planet. Seismic, volcanic, tsunami, mass wasting, flooding and sediment transport on the coasts all constitute significant hazards to the growing populations in coastal environments. GeoPRISMS projects have aimed to characterize the underlying physical mechanisms of these processes and this insight can yield a more considered and educated approach to responding and preparing for these events.

In particular GeoPRISMS projects have endeavored to describe the subsurface spatial distribution of melt underlying both subduction and rift volcanoes. This information is essential for future efforts to deduce the timing and size of potential eruptive episodes. One example of such a study is the iMUSH project which assembled an interdisciplinary group of investigators to image the magmatic architecture under Mount St. Helens, combining information from passive and active seismic measurements, magnetellurics, and petrologic investigations (e.g Kiser et al., 2016). This bottom to top study provides a snapshot of how melt is stored and how it is influenced by tectonic structure. Complimenting these approaches are investigations that examine the distribution of melt in time, and those that provide quantitative information about the timing of assembly of magmatic systems prior to eruption. One example of this sort of investigation was '*Assessing changes in the state of a magma storage system over caldera-forming eruption cycles, a case study at Taupo Volcanic Zone, New Zealand'*. This project examines magmatic system evolution in time encompassing large silicic eruptions and magmatic events before and after as way of better understanding the run-up to hazardous eruptions. GeoPRISMS projects have also contributed significantly to our understanding of pre-eruptive volatile contents and as volatiles provide the energy for eruptive episodes (e.g. Lloyd et al., 2016), understanding the volatile budget is important when making assessment of potential hazards.

Earthquakes (and the generation of tsunami) can be particularly hazardous in subduction zones and understanding how fault and rock properties modulate seismic hazards has been a primary motivator for many GeoPRISMS studies. For example, the *'Deep Mapping of the Megathrust on Land and at Sea around the Alaska Peninsula'* project team collected data on land and at sea to produce an image of the megathrust, constrain the properties of rocks around and within the megathrust, and linked fault properties to the earthquake history (e.g. Li et al., 2018). GeoPRISMS work also explores earthquake triggering phenomena and link between slow slip events and the potential for triggering earthquakes with destructive potential. In the '*Slow* *slip and future earthquake potential in New Zealand and Cascadia*' project the team has endeavored to generate a catalogue of slip events using GPS and sea floor vertical deformation and linking these observations to models with spatially variable elastic properties (Wallace et al., 2018). Finally, in addition to providing valuable information about the state of earthquake generating faults, GeoPRISMS projects have also facilitated instrument placement that has dual scientific and hazard response potential. For example, research interaction on the *'Faulting processes during early-stage rifting: analysis of an unusual earthquake sequence in northern Malawi'*, helped establish Malawi's first national seismic network (Shillington et al., 2016). Much like in the volcanic hazard, understanding the history of earthquakes and tsunamis is critical in understanding the risk associated with future events.

Mass wasting events and evolving coastlines also present significant geohazard events. Submarine slope failure at both passive and active margins can impact seafloor infrastructure and can generate tsunamis impacting the coastal environment (Dugan et al., 2015). For example, as part of ENAM multichannel seismic information was used to deduce detailed stratigraphy and structure in off-shore the Cape Fear submarine slide complex on the US Atlantic margin (Hill et al., 2018). The sediment supply and modifications of coastlines are rapidly impacting the environment for many coastal populations. Work on contemporary systems through GeoPRISMS give insight into interpreting the geologic record and also assess the rate of change to current alluvial fans and deltas (Straub and Esposito, 2013).

6. Education and Outreach.

The integration of Education and Outreach activities and cutting-edge science has been a priority for both the MARGINS and GeoPRISMS programs. Research projects on continental rifts and subduction zones have contributed important data sets and science discoveries that should become part of the Earth science teaching curriculum in universities. The MARGINS program therefore developed the mini-lessons, class room lectures that neatly incorporate the latest research on plate boundary processes, using the products of MARGINS-funded projects. Fifteen of these mini-lessons are currently available at the GeoPRISMS web page.

The GeoPRISMS program did not include an organized educational component, but over the course of ten years it has engaged students directly in science discussions through early-career symposiums. Another unique experience for many graduate students has been the participation in a community experiment. The 2009-2014 deployment and recovery of the Cascadia amphibious array, the 2014-2015 ENAM seismic project, the 2015-2016 geological field campaign to the Aleutians, and the 2018-2019 Alaska Amphibious Community Seismic Experiment gathered large and high-quality data sets for the GeoPRISMS community. These expeditions were designed to produce data for a range of related science goals, while making efficient use of the available resources, such as ships and other logistical support, and national facilities. The investigator teams also recruited students from any university to participate in land-based and ship-based expeditions through an application process. The GeoPRISMS office has played an important role in advertising and facilitating these projects.

7. Legacy of GeoPRISMS data.

The MARGINS and GeoPRISMS decadal programs have funded and facilitated acquisition of geophysical, geochemical and petrological data in a number of focus sites. Archiving of these valuable data sets and meta-data has improved steadily over the years. They are available through various data portals, such as IEDA, IRIS and UNAVCO. Open access of these data serves many purposes: 1) Some GeoPRISMS goals are best addressed in comparative studies of plate boundary processes, which may require data from multiple focus sites, 2) new data analysis methods can lead to data mining projects that utilize these legacy data sets, 3) high-profile science publications should be supported by data sets that are publicly available, such that the results can be reproduced, and 4) archived data sets can be used for training new scientists.

Over the years, the IEDA team has improved data management support for the GeoPRISMS community to the need for integration of various data types, and global syntheses. Geodesy, active-source seismic data, heat flow data, magnetotelluric data, rock chemistry, fluid chemistry, and petrology data can all be accessed on several of the focus sites. A catalog of MARGINS and GeoPRISMS funded studies, a bibliographic database, and the GeoMapApp data visualization all make it easier to access and use these data. Since many GeoPRISMS projects are still ongoing, the number of inventoried data sets (170) still lags the MARGINS program (480). A strong commitment to archiving these data sets will be an important step towards the completion and synthesis of the GeoPRISMS program.

8. Integration of GeoPRISMS science results from various disciplines.

Discussion related to the integration of GeoPRISMS science results were lively and enthusiastic. Overall the value of integrative projects was emphasized. Discussion centered around two main topics, the process of integrating results, and outcomes.

Most discussion about integrating results focused on the need for workshops. Rationale for both geographically focused and topical focused workshops were recognized. There was acknowledgment that GeoPRISMS had rapidly collected a lot of different kinds of data at each focus site. Participants felt that one good way to integrate and synthesize these results, thereby capitalizing on the focus site approach, would be through focus site workshops. Primary goals of these workshops could be to present preliminary results by addressing what data we have, what we have learned, and what data gaps remain. At the same time these workshops would provide opportunities for scientists working at the same focus sites to connect across the different experiments and learn from other perspectives. Because funding for each focus site was phased, the focus site workshops might be similarly phased. A nested approach was also suggested with each focus site having their own workshop and then a combined workshop for SCD and RIE focus sites.

Some common themes that emerged from discussions of topical workshops included the water and carbon cycle in the solid Earth, fluid transport and volatiles, interpretation of seismic velocities, deformation at plate boundaries, the impact of structural inheritance and healing on tectonics, rock physics. Important themes for each of these topical discussions would be strategies for spatial and temporal integration. The advantage of topical workshops is that they have the potential of integrating a lot of knowledge across a wide breadth of disciplines.

Integration outcomes focused on educational material at all levels, K-graduate school. At the K-12 level publically available websites and other educational materials synthesizing results is recognized as a need. At higher educational levels discussions about the relative advantages and pitfalls of developing textbooks versus so-called 'living' documents that are updated frequently (e.g., Wikipedia and the like) were discussed. The advantages of thematic journal collections in which papers are compiled in a single source but published when they are ready were discussed. The major advantage of this approach is that is gets around the long lead-time it often takes for single volumes to come out. The role of animations as an educational tool and the benefits of taped lectures in facilitating classroom discussions were discussed.

Finally, participants discussed the importance of accessible and citable data and samples as being crucial to future work. These datasets can often be used for multiple applications and purposes. The need for access to processed data was also highlighted.

9. Opportunities to collaborate with allied organizations

The range of allied organizations that engage in GeoPRISMS related research is broad both nationally and internationally. Leveraging their expertise and resources contributes materially to the achievement of GeoPRISMS goals. Representatives from NASA, the USGS, and IODP made presentations focused on GeoPRISMS related science within their organizations.

An important NASA initiative is 'Earth Surface and Interior (ESI)' (Davis et al., 2015). This focus area targets research and analysis of solid-Earth processes and properties with the overarching goal of better understanding the structure, dynamics, and interaction of the core, mantle, and lithosphere. ESI also explores the interactions between the solid Earth and processes related to Earth's fluid envelopes using NASA spaceborne sensor capabilities. Overarching themes within the ESI focus area related to GeoPRISMS include 1) deformation associated with plate boundary processes and implications for earthquakes, tsunamis and other related natural hazards; 2) relationships between tectonic processes and climate variability that shape Earth's surface and create natural hazards, 3) the evolution of magmatic systems and related hazards, and 4) the response of Earth's surface to the deep interior. A number of ongoing and upcoming missions have the capability of informing directly GeoPRISMS science questions. Highlighted missions include GRACE-FO (Gravity Recovery and Climate Experiment – Follow-On), NISAR (NASA-Indian Space Research organization synthetic aperture radar mission), and SWOT (Surface water ocean topography mission). Additionally, the GeoPRISMS community has the opportunity to impact NASA observational and data needs priorities by getting involved in NASA's Decadal Survey implementation.

Opportunities for collaborations with the USGS focused on subduction zone science tied to assessing and reducing risk to natural hazards (Gomberg et al., 2017). Important USGS themes related to GeoPRISMS include improving observations and models of subduction zone processes, and analyzing natural hazards and risk. Within the USGS these themes are being addressed through focused studies of the Cascadia and Alaskan subduction zones and monitoring and characterizing their volcanic arcs. Highlighted areas of overlap include: 1) distinguishing between different Cascadia megathrust earthquake recurrence models; 2) measuring transient slow slip on the seafloor; 3) observing slip over millennia via lake cores; 4) volcanic processes; and 5) interactions between upper plate offshore structure and plate interface properties and slip.

IODP science related to GeoPRISMS falls under the 'Earth Connections', and 'Earth in Motion' themes (International Ocean Discovery Program, 2011). The 'Earth Connections' science theme emphasizes the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater, subduction zone initiation, recycling of volatiles through the deep mantle, and the origin of continental crust. The 'Earth in Motion' theme emphasizes questions related to mechanisms that control the occurrence of destructive earthquakes, landslides, and tsunamis, and how fluids link subseafloor tectonic, thermal, and biogeochemical processes. The GeoPRISMS community has the opportunity to impact IODP science through as the post-2023 science plan is developed.

10. Steps necessary for synthesis of GeoPRISMS

Synthesis of the GeoPRISMS program requires that the analysis of data, and the organization of these analyses into a framework of internally-consistent interpretations. This type of synthesis is beyond the scope of any PI or even a small group of PIs. Indeed, the breadth of disciplines involved in GeoPRISMS research necessitates a careful, inclusive, and iterative approach. In addition, the staged funding approach for the five primary sites has helped the community organize field projects, but it also means that the science results in Cascadia and the Aleutians are more mature than in the EARS and New Zealand, where data acquisition is just ending. The goals of the RIE and SCD Initiatives can only be met by combining the outcomes of all these primary sites.

Participants in the GeoPRISMS TEI propose that synthesis of GeoPRISMS data will require continued investment in small conferences and workshops. These workshops may focus on topics of regional importance, for example one or more of the GeoPRISMS primary sites. Additional workshops may direct interdisciplinary focus towards more specific sets of key processes. The objective of these workshops would be to identify where the observations and interpretations of disparate stakeholders agree or disagree. Diagrammatically, these workshops should appear as a web, with individual participants encouraged to attend several workshops crossing disciplinary boundaries. Examples of some topical workshops include:

- Origin and evolution of plate boundaries
- Linking geophysical imaging to active composition/state/properties
- Fluids/metamorphism/rheology
- Fluid and volatile migration
- Fluxes, physics, and finding serpentinite
- Feedbacks between tectonic deformation and magmatism
- Exhumed records of plate margins at depth
- The pace and mechanisms of magma supply
- From slow slip to mega-earthquakes
- Coupling geodynamics and surface processes
- Geohazards on passive-aggressive margins

Additional synthesis and engagement of early career scientists would be facilitated by longer format meetings, such as a CIDER-style summer program. A CIDER-style program would encourage students and postdocs to interact with faculty at all career stages to define new projects that exploit data collected during the GeoPRISMS program. Managing these conferences would require some infrastructure, likely including a continuation of the GeoPRISMS office.

11. Steps necessary to keep community engaged beyond the GeoPRISMS program

Over the course of the TEI, discussions among scientists and students showed that there is a great interest in the community to investigate geological processes at plate boundaries with in interdisciplinary approach. In the last breakout session of the TEI, participants organized in several groups to explore how a few focused working groups may carry on GeoPRISMS-related research, using all possible data and modeling approaches. Each of these groups produced a short overview of the science questions of interest, possible target areas for research, and a plan to organize the community.

1) *Origin and evolution of plate boundaries.* Which factors control the origin and evolution of plate boundaries? Research can focus on any subduction zones, transform boundaries and continental rifts.
2) *Linking geophysical images to Earth's composition, state, and physical properties.* Imaged seismic and electrical properties can be used by experimentalists and theoreticians to investigate state variables, such as composition, temperature, fluid phase and content, grain size, and deformation mechanisms.
3) *Fluids, metamorphism, rheology, and exhumed records of plate margins.* How does the rheology of the plate interface evolve through the seismogenic zone and beyond?
4) *Fluid and volatile migration.* What controls the pathways and mechanisms for fluid transport?
5) *Feedbacks between tectonic deformation and magmatism.* What is the cause and effect in interactions between lithospheric deformation and magmatic processes?
6) *The pace and mechanics of magma supply.* What controls the location of magma generation and flux to the surface? What observations can we use as a proxy for magma flux?
7) *From slow slip to mega-earthquakes.* How do we link stress state, fault strength and the mode of slip at plate boundaries? What is the role of sedimentary structures in plate coupling?
8) *Coupling of geodynamics and surface processes. Geohazards on passive-aggressive margins.* What feedbacks between tectonic and surface processes produce the observed sediment flux, stratigraphy, at different spatial and temporal scales?

In each of these discussions, scientists emphasized the need to maintain the connections that the GeoPRISMS office has provided for our community over the past ten years. Focused workshops will help to set new science goals and to forge collaborations between scientists and students from different disciplines. Given the complexity of the research topics, future multidisciplinary studies of Earth's plate boundaries will be essential to move the science forward.

References

Accardo, N. J., D. J. Shillington, J. B. Gaherty, C. A. Scholz, A. A. Nyblade, P. R. N. Chindandali, G. Kamihanda, T. McCartney, D. Wood, and R. W. Ferdinand (2018), Constraints on rift basin structure and border fault growth in the northern Malawi rift from 3- D seismic refraction imaging, *J. Geophys. Res. Solid Earth*, *123*, 10,003-010,025, doi:10.1029/2018JB016504.

Anderson, K. R., and M. P. Poland (2017), Abundant carbon in the mantle beneath Hawai‘i, *Nature Geosci.*, *10*, 704-708, doi:10.1038/ngeo3007.

Axen, G. J., J. W. van Wijk, and C. A. Currie (2018), Basal continental mantle lithosphere displaced by flat-slab subduction, *Nature Geosci.*, *11*, 961-964, doi:10.1038/s41561-018-0263-9.

Bedrosian, P. A., J. R. Peacock, E. Bowles-Martinez, A. Schultz, and G. J. Hill (2018), Crustal inheritance and a top-down control on arc magmatism at Mount St Helens, *Nature Geosci.*, *11*, 865–870, doi:10.1038/s41561-018-0217-2.

Beutel, E., J. van Wijk, C. Ebinger, D. Keir, and A. Agostini (2010), Formation and stability of magmatic segments in the Main Ethiopian and Afar rifts, *Earth Planet. Sci. Lett.*, *293*, 225-235, doi:10.1016/j.epsl.2010.02.006.

Bialas, R. W., W. R. Buck, and R. Qin (2010), How much magma is required to rift a continent?, *Earth Planet. Sci. Lett.*, *292*, 68-78, doi:10.1016/j.epsl.2010.01.02.

Birhanu, Y., R. Bendick, S. Fisseha, E. Lewi, M. Floyd, R. King, and R. Reilinger (2016), GPS constraints on broad scale extension in the Ethiopian Highlands and Main Ethiopian Rift, *Geophys. Res. Lett.*, *43*, 6844-6851, doi:10.1002/2016GL069890.

Brounce, M. N., K. A. Kelley, and E. Cottrell (2014), Variations in $Fe^{3+}/\sum Fe$ of Mariana Arc Basalts and Mantle Wedge fO_2 *J. Petrol.*, *55*, 2513-2536, doi:10.1093/petrology/egu065.

Canales, J. P., S. M. Carbotte, M. R. Nedimović, and H. Carton (2017), Dry Juan de Fuca slab revealed by quantification of water entering Cascadia subduction zone, *Nature Geosci.*, *10*, 864–870, doi:10.1038/ngeo3050.

Cline, C. J., U. H. Faul, E. C. David, A. J. Berry, and I. Jackson (2018), Redox-influenced seismic properties of upper-mantle olivine, *Nature*, *555*, 355-358, doi:10.1038/nature25764.

Cooper, K. M., and A. J. R. Kent (2014), Rapid remobilization of magmatic crystals kept in cold storage, *Nature*, *506*, 480-483 doi:10.1038/nature12991.

Corti, G., J. van Wijk, S. Cloetingh, and C. K. Morley (2007), Tectonic inheritance and continental rift architecture: Numerical and analogue models of the East African Rift system, *Tectonics*, *26*(6), Tc6006, doi:10.1029/2006tc002086.

Currie, C. A., and J. van Wijk (2016), How craton margins are preserved: Insights from geodynamic models, *J. Geodyn.*, *100*, 144-158, doi:10.1016/j.jog.2016.03.015.

Davis, J. L., L. H. Kellogg, J. R. Arrowsmith, B. A. Buffett, C. G. Constable, A. Donnellan, E. R. Ivins, G. S. Mattioli, S. E. Owen, M. E. Pritchard, M. E. Purucker, D. T. Sandwell, and J. Sauber (2016), Challenges and Opportunities for Research in ESI (CORE): Report from the NASA Earth Surface and Interior (ESI) Focus Area Workshop, November 2–3, 2015, Arlington, Virginia, 88 pp.

Dillon, W. P., and P. Popenoe (1988), The Blake Plateau Basin and Carolina Trough, in *The Geology of North America, Vol. I-2, The Atlantic Continental Margin, U.S.*, edited by R. E. Sheridan, and J.A. Grow, pp. 291–328, Geological Society of America, Boulder, Colo., doi:10.1130/DNAG-GNA-I2.291.

Dugan, B., Abeyta, A., Paola, C., Lynch, W.G., 2015. Exploring Submarine Mass Failures with Physical Experiments and Numerical Models, AGU Fall Meeting Abstracts.

Ebinger, C. J., T. Yemane, G. Woldegabriel, J. L. Aronson, and R. C. Walter (1993), Late Eocene–Recent volcanism and faulting in the southern main Ethiopian rift, *J. Geol. Soc. London*, *150*, 99-108, doi:10.1144/gsjgs.150.1.0099.

Ebinger, C., A. Ayele, D. Keir, J. Rowland, G. Yirgu, T. Wright, M. Belachew, and I. Hamling (2010), Length and timescales of rift faulting and magma intrusion: The Afar rifting cycle from 2005 to present, *Ann. Rev. Earth Planet. Sci.*, *38*, 439-466, doi:10.1146/annurev-earth-040809-152333.

Ebinger, C. J., D. Keir, I. D. Bastow, K. Whaler, J. O. S. Hammond, A. Ayele, M. S. Miller, C. Tiberi, and S. Hautot (2017), Crustal structure of active deformation zones in Africa: Implications for global crustal processes, *Tectonics*, *36*, 3298-3332, doi:10.1002/2017TC004526.

Fischer, T. P., P. Burnard, B. Marty, D. R. Hilton, E. Füri, F. Palhol, Z. D. Sharp, and F. Mangasini (2009), Upper-mantle volatile chemistry at Oldoinyo Lengai volcano and the origin of carbonatites, *Nature*, *459*, 77–80, doi:10.1038/nature07977.

Foley, S. F., and T. P. Fischer (2017), An essential role for continental rifts and lithosphere in the deep carbon cycle, *Nature Geosci.*, *10*, 897-902, doi:10.1038/s41561-017-0002-7.

Gaherty, J. B., et al. (2019), Faulting processes during early-stage rifting: seismic and geodetic analysis of the 2009–2010 Northern Malawi earthquake sequence, *Geophys. J. Int.*, *217*, 1767-1782, doi:10.1093/gji/ggz119.

Gazel, E., et al. (2015), Continental crust generated in oceanic arcs, *Nature Geosci.*, *8*, 321-327, doi:doi:10.1038/ngeo2392.

Gomberg, J.S., Ludwig, K.A., Bekins, B.A., Brocher, T.M., Brock, J.C., Brothers, Daniel, Chaytor, J.D., Frankel, A.D., Geist, E.L., Haney, Matthew, Hickman, S.H., Leith, W.S., Roeloffs, E.A., Schulz, W.H., Sisson, T.W., Wallace, Kristi, Watt, J.T., Wein, Anne, (2017), Reducing risk where tectonic plates collide—U.S. Geological Survey subduction zone science plan: U.S. Geological Survey Circular 1428, 45 p., https://doi.org/10.3133/cir1428.

Han, S., S. M. Carbotte, J. P. Canales, M. R. Nedimović, and H. Carton (2018), Along- Trench Structural Variations of the Subducting Juan de Fuca Plate From Multichannel Seismic Reflection Imaging, *J. Geophys. Res. Solid Earth*, *123*, 3122-3146, doi:10.1002/2017JB015059.

Hill, J. C., D. S. Brothers, M. J. Hornbach, D. E. Sawyer, D. J. Shillington, and A. Bécel (2018), Subsurface controls on the development of the Cape Fear Slide Complex, central US Atlantic Margin, edited, Geological Society Special Publications 477, London, doi:10.1144/SP477.17.

Holbrook, W. S., G. M. Purdy, R. E. Sheridan, L. Glover, III, M. Talwani, J. Ewing, and D. Hutchinson (1994), Seismic structure of the U.S. Mid-Atlantic continental margin, *J. Geophys. Res.*, *99*, 17,871-817,891, doi:10.1029/94JB00729.

International Ocean Discovery Program (2011) Illuminating Earth's Past, Present and Future: The Science Plan for the International Ocean Discovery Program 2013–2023. Washington, DC: Integrated Ocean Drilling Program Management International.

Kelemen, P. B., and C. E. Manning (2015), Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up, *Proc. Nat. Acad. Sci.*, *112*, E3997-E4006, doi:10.1073/pnas.1507889112.

Kiser, E., I. Palomeras, A. Levander, C. Zelt, S. Harder, B. Schmandt, S. Hansen, K. Creager, and C. Ulberg (2016), Magma reservoirs from the upper crust to the Moho inferred from high-resolution Vp and Vs models beneath Mount St. Helens, Washington State, USA, *Geology*, *44*, 411-414, doi:doi:10.1130/G37591.1.

Li, J., D. J. Shillington, D. M. Saffer, A. Bécel, M. R. Nedimović, H. Kuehn, S. C. Webb, K. M. Keranen, and G. A. Abers (2018), Connections between subducted sediment, pore-fluid pressure, and earthquake behavior along the Alaska megathrust, *Geology*, *46*, 299-302, doi:10.1130/G39557.1.

Li, S., and J. T. Freymueller (2018), Spatial variation of slip behavior beneath the Alaska peninsula along Alaska- Aleutian subduction zone, *Geophys. Res. Lett.*, *45*, 3453-3460, doi:10.1002/2017GL076761.

Lloyd, A. S., E. Ferriss, P. Ruprecht, E. H. Hauri, B. R. Jicha, and T. Plank (2016), An assessment of clinopyroxene as a recorder of magmatic water and magma ascent rate, *J. Petrol.*, *57*, 1865-1886, doi:10.1093/petrology/egw058.

Lynner, C., and M. Bodmer (2017), Mantle flow along the eastern North American margin inferred from shear wave splitting, *Geophys. Res. Lett.*, *45*, 867-870, doi:10.1130/G38980.1.

Mao, X., M. Gurnis, and D. A. May (2017), Subduction initiation with vertical lithospheric heterogeneities and new fault formation, *Geophys. Res. Lett.*, *44*, 11,349-311,356, doi:10.1002/2017GL075389.

Mazza, S. E., E. Gazel, E. A. Johnson, M. Bizimis, R. McAleer, and C. B. Biryol (2017), Post-rift magmatic evolution of the eastern North American “passive-aggressive” margin, *Geochem. Geophys. Geosyst.*, *18*, 3–22, doi:10.1002/2016GC006646.

Muirhead, J. D., S. A. Kattenhorn, H. L. S. Mana, B. D. Turrin, T. P. Fischer, G. Kianji, E. Dindi, and D. S. Stamps (2016), Evolution of upper crustal faulting assisted by magmatic volatile release during early-stage continental rift development in the East African Rift, *Geosphere*, *12*, 1670-1700, doi:10.1130/GES01375.1.

Nielsen, S. G., and H. R. Marschall (2017), Geochemical evidence for mélange melting in global arcs, *Sci. Adv.*, *3*, e1602402, doi:10.1126/sciadv.1602402.

Nooner, S. L., L. Bennati, E. Calais, W. R. Buck, I. J. Hamling, T. J. Wright, and E. Lewi (2009), Post- rifting relaxation in the Afar region, Ethiopia, *Geophys. Res. Lett.*, *36*, L21308, doi:10.1029/2009GL040502.

Perrin, A., Goes, S., Prytulak, J., Davies, D.R., Wilson, C., Kramer, S., 2016. Reconciling mantle wedge thermal structure with arc lava thermobarometric determinations in oceanic subduction zones. Geochemistry, Geophysics, Geosystems, 17(10): 4105-4127.

Rees Jones, D.W., Katz, R.F., Tian, M., Rudge, J.F., 2018. Thermal impact of magmatism in subduction zones. Earth and Planetary Science Letters, 481: 73-79.

Reyners, M., D. Eberhart-Phillips, and S. Bannister (2017), Subducting an old subduction zone sideways provides insights into what controls plate coupling, *Earth Planet. Sci. Lett.*, *466*, 53-61, doi:10.1016/j.epsl.2017.03.004.

Rooney, T. O., I. D. Bastow, D. Keir, F. Mazzarini, E. Movsesian, E. B. Grosfils, J. R. Zimbelman, M. S. Ramsey, D. Ayalew, and G. Yirgu (2014), The protracted development of focused magmatic intrusion during continental rifting, *Tectonics*, *33*, 875-897, doi:10.1002/2013TC003514.

Rooney, T. O., A. Lavigne, C. Svoboda, G. Girard, G. Yirgu, D. Ayalew, and J. Kappelman (2017), The making of an underplate: Pyroxenites from the Ethiopian lithosphere, *Chem. Geol.*, *455*, 264-281, doi:10.1016/j.chemgeo.2016.09.011.

Rubin, A.E., Cooper, K.M., Till, C.B., Kent, A.J.R., Costa, F., Bose, M., Gravley, D., Deering, C., Cole, J., 2017. Rapid cooling and cold storage in a silicic magma reservoir recorded in individual crystals. Science, 356(6343): 1154-1156.

Ruprecht, P., and T. Plank (2013), Feeding andesitic eruptions with a high-speed connection from the mantle, *Nature*, *500*, 68-72, doi:10.1038/nature12342.

Rychert, C. A., J. O. S. Hammond, N. Harmon, J. M. Kendall, D. Keir, C. Ebinger, I. D. Bastow, A. Ayele, M. Belachew, and G. Stuart (2012), Volcanism in the Afar Rift sustained by decompression melting with minimal plume influence, *Nature Geosci.*, *5*, 406-409, doi:10.1038/ngeo1455.

Shillington, D. J., A. Bécel, M. R. Nedimović, H. Kuehn, S. C. Webb, G. A. Abers, K. M. Keranen, J. Li, M. Delescluse, and G. A. Mattei-Salicrup (2015), Link between plate fabric, hydration and subduction zone seismicity in Alaska, *Nature Geosci.*, *8*, 961-964, doi:10.1038/ngeo2586.

Shillington, D. J., et al. (2016), Acquisition of a Unique Onshore/Offshore Geophysical and Geochemical Dataset in the Northern Malawi (Nyasa) Rift, *Seismol. Res. Lett.*, *87*, 1406-1416, doi:10.1785/0220160112.

Stern, R. J., and D. W. Scholl (2010), Yin and yang of continental crust creation and destruction by plate tectonic processes, *Int. Geol. Rev.*, *52*, 1-31, doi:10.1080/00206810903332322.

Straub, K. M., and C. R. Esposito (2013), Influence of water and sediment supply on the stratigraphic record of alluvial fans and deltas: Process controls on stratigraphic completeness, *J. Geophys. Res. Earth Surface*, *118*, 625-637, doi:10.1002/jgrf.20061.

van Wijk, J., J. van Hunen, and S. Goes (2008), Small-scale convection during continental rifting: Evidence from the Rio Grande rift, *Geology*, *36*, 575–578, doi:10.1130/G24691A.1.

van Wijk, J. W., W. S. Baldridge, J. van Hunen, S. Goes, R. Aster, D. D. Coblentz, S. P. Grand, and J. Ni (2010), Small-scale convection at the edge of the Colorado Plateau: Implications for topography, magmatism, and evolution of Proterozoic lithosphere, *Geology*, *38*(7), 611-614, doi:10.1130/g31031.1.

Vogt, K., Castro, A., Gerya, T., 2013. Numerical modeling of geochemical variations caused by crustal relamination. Geochemistry, Geophysics, Geosystems, 14(2): 470-487.

Wallace, L. M., Å. Fagereng, and S. Ellis (2012), Upper plate tectonic stress state may influence interseismic coupling on subduction megathrusts, *Geology*, *40*, 895-898, doi:10.1130/G33373.1 .

Wallace, L. M., S. C. Webb, Y. Ito, K. Mochizuki, R. Hino, S. Henrys, S. Y. Schwartz, and A. F. Sheehan (2016), Slow slip near the trench at the Hikurangi subduction zone, New Zealand, *Science*, *352*, 701-704, doi:10.1126/science.aaf2349.

Wallace, L. M., S. Hreinsdóttir, S. Ellis, I. Hamling, E. D'Anastasio, and P. Denys (2018), Triggered Slow Slip and Afterslip on the Southern Hikurangi Subduction Zone Following the Kaikōura Earthquake, *Geophys. Res. Lett.*, *45*, 4710-4718, doi:10.1002/2018GL077385.

Walowski, K. J., P. J. Wallace, E. H. Hauri, I. Wada, and M. A. Clynne (2015), Slab melting beneath the Cascade Arc driven by dehydration of altered oceanic peridotite, *Nature Geosci.*, *8*, 404-408, doi:10.1038/ngeo2417.

Whalen, L., E. Gazel, C. Vidito, J. Puffer, M. Bizimis, W. Henika, and M. J. Caddick (2015), Supercontinental inheritance and its influence on supercontinental breakup: The Central Atlantic Magmatic Province and the breakup of Pangea, *Geochem. Geophys. Geosyst.*, *16*, 3532-3554, doi:10.1002/2015GC005885.

Wilson, C.R., Spiegelman, M., van Keken, P.E., Hacker, B.R., 2014. Fluid flow in subduction zones: The role of solid rheology and compaction pressure. Earth and Planetary Science Letters, 401: 261-274.

Winterbourne, J., A. Crosby, and N. White (2009), Depth, age and dynamic topography of oceanic lithosphere beneath heavily sedimented Atlantic margins, *Earth Planet. Sci. Lett.*, *287*, 137-151, doi:10.1016/j.epsl.2009.08.019.

Withjack, M. O., R. W. Schlische, and P. E. Olsen (1998), Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America: An analog for other passive margins, *Am. Assoc. Petrol. Geol. Bull.*, *82*(5), 817-835, doi:10.1306/1D9BC60B-172D-11D7-8645000102C1865D.